Design and Analysis of Hybrid Solar Lighting and Full-Spectrum Solar Energy Systems

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DESIGN AND ANALYSIS OF HYBRID SOLAR LIGHTING AND FULL-SPECTRUM SOLAR ENERGY SYSTEMS

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ABSTRACT

This paper describes a systems-level design and analysis of a new approach for improving the energy efficiency and affordability of solar energy in buildings, namely, hybrid solar lighting and full-spectrum solar energy systems. By using different portions of the solar spectrum simultaneously for multiple end-use applications in buildings, the proposed system offers unique advantages over other alternatives for using sunlight to displace electricity (conventional topside daylighting and solar technologies). Our preliminary work indicates that hybrid solar lighting, a method of collecting and distributing direct sunlight for lighting purposes, will alleviate many of the problems with passive daylighting systems of today, such as spatial and temporal variability, glare, excess illumination, cost, and energy efficiency. Similarly, our work suggests that the most appropriate use of the visible portion of direct, nondiffuse sunlight from an energy-savings perspective is to displace electric light rather than generate electricity.

Early estimates detailed in this paper suggest an anticipated system cost of well under $2.0/Wp and 5-11 ¢/kWh for displaced and generated electricity in single-story commercial building applications. Based on a number of factors discussed in the paper, including sunlight availability, building use scenarios, time-of-day electric utility rates, cost, and efficacy of the displaced electric lights, the simple payback of this approach in many applications could eventually be well under 5 years.

INTRODUCTION

Throughout the 1900s, the use of the sun as a light source for illuminating building interiors has evolved considerably. As we entered the century, the sun was our primary source of interior light during the day. Eventually, however, the cost and performance of electric lamps improved, and the sun was displaced as our primary method of lighting building interiors. During the oil embargo of the 1970s, a renewed interest in daylighting emerged, yet that interest was outweighed by the convenience and cost of electric light sources that could be placed virtually anywhere in a building. Further, the disadvantages of conventional daylighting systems (glare, variability, difficulty of control, required architectural modifications, and excessive illuminance) were quickly exposed.

In recent years, however, a few technologies have made daylight harvesting a reality for some applications. For example, dimming ballasts are in widespread use in conjunction with perimeter fenestration systems to reduce electric lamp energy consumption. Today, topside daylighting approaches are designed to reduce glare and variability, minimize the need for control, and eliminate excessive illuminances. In doing so, however, they typically waste a significant portion of the natural light available by shading, attenuating, and or diffusing direct sunlight. Because more than 80% of the light available on a sunny day is in the form of direct sunlight,[1] the energy end-use efficiency of state-of-the-art daylighting systems is therefore low, and the associated simple payback is relatively high in comparison to other energy-efficiency measures. This limits the market penetration of such systems and their utility to save significant amounts of nonrenewable energy.

For decades, researchers have also been developing approaches for harnessing the renewable energy of the sun through electricity generation. To date, several approaches have been used to extract energy from sunlight and convert it into usable electrical power, including photovoltaics (PVs) (commonly known as solar cells) and solar thermal electric systems. These technologies are finding more widespread uses and most experts agree that the simplicity, versatility, and low environmental impact will ultimately help these technologies become an important source of economical power in the new millennium.

Unfortunately, widespread use of solar technologies is still limited by their relative cost, performance, and energy density when compared to existing nonrenewable energy sources. One of the primary technical barriers is that in many portions of the solar spectrum, even the most cost-effective solar cells (those using silicon) and solar thermal systems are somewhat inefficient when converting light into electricity. Figure 1 illustrates this problem in the case of silicon-based devices. In the high-frequency portion of the ultraviolet and visible spectrum, the responsivity of silicon-based materials is relatively low.

To overcome these barriers, one approach has been to develop utility-scale PV and solar thermal concentrators. By using concentrators, the cell area and, consequently, cell cost can be reduced by approximately the same amount as the desired concentration ratio (10:1 to 1000:1). Unfortunately, this cost-savings is typically offset by the added cost and complexity of the required tracking system used to collect direct, nondiffuse sunlight. For these reasons, the market penetration of solar electric technologies and their subsequent use to save significant amounts of nonrenewable energy is severely limited.

The luminous efficacy of direct sunlight is ~90 to 100 lm/W depending on the sun's orientation relative to the earth. Interestingly, the luminous efficacy of *filtered* visible sunlight (180 - 200 lm/W) far exceeds existing electric lamps (15 - 90 lm/W). Therein lies the primary benefit and motivation for using filtered, direct, nondiffuse, visible sunlight for interior lighting purposes. Its luminous efficacy is typically more than double its electric competition. As such, though the energy density of solar energy is lower than nonrenewables, the "luminous energy density" of filtered sunlight is more than twice better than its only other competition for interior lighting of buildings, namely electric lights (artificial lighting is exclusively an electric technology). Our work indicates that passive distribution and use of the visible portion of solar energy is the preferred use of solar energy when nonrenewable energy displacement (see Figure 2), cost-effectiveness, and lighting quality are the primary deployment drivers.

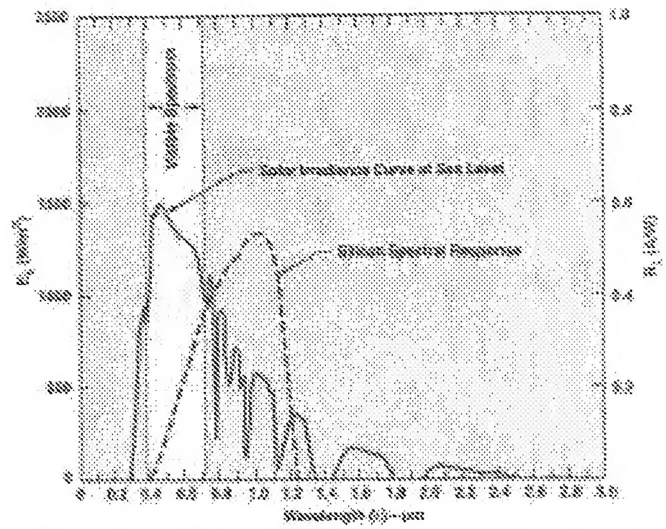

Figure 1. Approximate spectral radiance E_λ of the sun at mean earth-sun separation and silicon spectral response (R_λ).

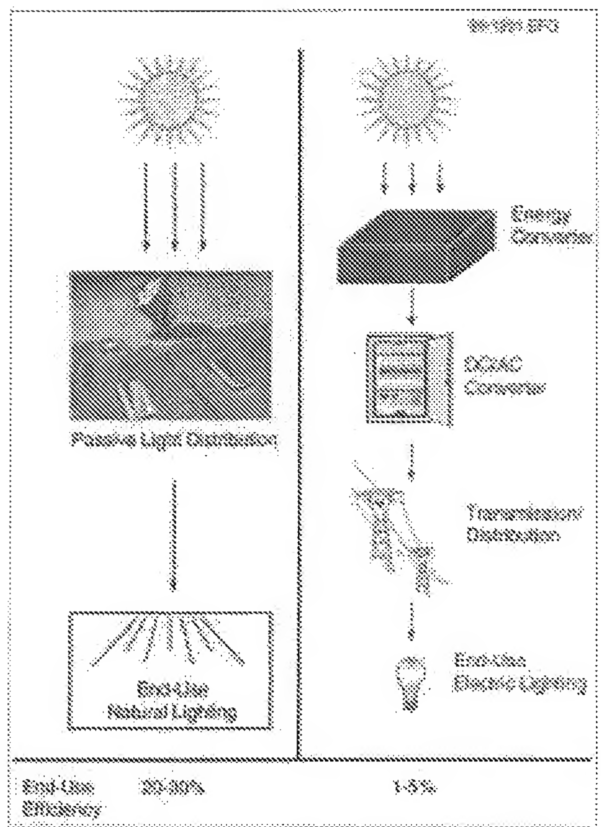

Figure 2. Comparative analysis of uses of sunlight for interior lighting applications.

PHYSICAL DESCRIPTION OF HYBRID LIGHTING SYSTEMS

Hybrid lighting systems consist of five major elements: (1) light sources (both sunlight and electric lamps), (2) sunlight collection and tracking systems, (3) light distribution systems, (4) hybrid lighting control systems, and (5) hybrid luminaires. Figure 3 illustrates a typical hybrid lighting configuration.

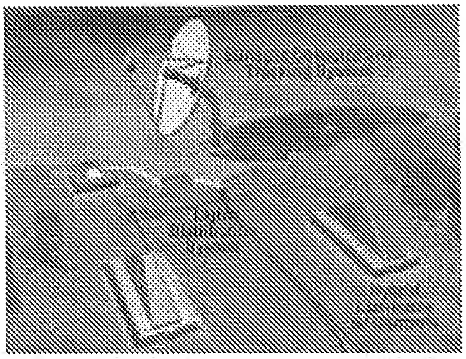

Figure 3. Major elements of hybrid lighting systems.

Natural light sources – Sunlight represents one of the earth's primary sources of nonrenewable energy and is a primary light source for hybrid solar lighting systems. Direct sunlight contributes approximately four-fifths of the total illuminance at the earth's surface and has an approximate color temperature of 6000°K. The illuminance on a horizontal surface at sea level, with the sun at its zenith in a clear sky is

$$E = 1.24 \times 10^5 \text{ lux } (\text{lm m}^{-2}).$$

The remaining one-fifth of the total illuminance at the earth's surface is from the sky, that is, from sunlight scattered by the earth's atmosphere. Because the proposed system tracks the sun, hybrid solar lighting systems use only direct, nondiffuse sunlight, but in doing so, they use the dominant source of natural light more efficiently.

Luminaire and remotely located electric lamps – Hybrid lighting systems will depend on electric lamps when sunlight is incapable of supplying sufficient levels of illumination such as on cloudy, overcast days and at night. Electric lamps used in hybrid lighting systems must either be located in (or near) a hybrid luminaire or, in some cases, may be located at remote locations along with the natural light sources. As such, electric lamps used in hybrid systems will not be of one particular type and may differ from application-to-application, depending on the system requirements.

Early applications of hybrid lighting systems will be in commercial buildings where lighting is the single largest use of electricity and will likely incorporate conventional fluorescent lamps located in luminaires.[2] As performance and cost improvements are made in light distribution systems, some applications of hybrid lighting may transition to systems using remotely located electric lamps.

Light collection systems – Because hybrid lighting incorporates direct sunlight, it includes two-axis, tracking, light collection systems. Unfortunately, the sun's position relative to the earth changes constantly. Later, we describe an integrated hybrid lighting system design that uses a two-axis, tracking parabolic dish concentrator.

It is important to note, however, that the spatial illumination variability inherent to conventional topside daylighting throughout the day is eliminated in hybrid systems because the light will always emerge in the room at the same place traveling the same direction. Temporal variability will be minimized because hybrid luminaires will continuously adjust electric lighting based on the amount of sunlight available.

Light distribution systems – Once collected, several options exist for transmitting light to the interior of buildings:

- large-core optical fibers – waveguides that transmit light via total internal reflection and are typically fabricated using flexible materials such as solid polymers, gels, and liquids;
- fiber optic bundles – a series of small glass or plastic optical fibers bundled together to form the equivalent of a large-core optical fiber; and
- hollow-core reflective lightpipes – hollow lightpipes that are typically cylindrical in shape and coated with a highly-reflective material to transmit light via multiple reflections off interior wall surfaces.

Because of their flexibility, cost, ease of installation, and performance, early hybrid lighting system designs incorporate large-core optical fibers.

Hybrid lighting control systems – Hybrid lighting systems will employ lighting control systems for several reasons. First, to reduce the use of electric light and save energy, daylight harvesting control systems similar to those found in conventional perimeter daylight harvesting systems will be required. Second, in some applications, the need for hybrid lighting color control systems that alter the effective color temperature and color rendering index of natural light emerging from hybrid luminaries may be required. Third, the need for task dimming and on/off controls for both natural and electric sources will be required for some interior lighting applications based on occupant preferences .

Hybrid luminaires – Hybrid lighting systems incorporate light originating from two or more sources, at least one being natural and another being electric. As such, hybrid luminaires capable of distributing and blending light from both sources must be developed. They must minimize light loss factors and ensure a relatively constant spatial/temporal distribution, color, and coefficient of utilization (CU) no matter which light sources are in use.

Preliminary Design of Sunlight Collector

Three design scenarios for lighting-based sunlight collection systems were identified. The first design approach incorporates a two-axis, tracking, solar concentrator scheme that uses Fresnel lenses to focus sunlight directly onto a series of optical fibers, as illustrated in Figure 4. This design was originally developed for concentrating PV systems and is a modest revision and improvement to a similar design approach originally introduced by Himawara Corp. in Japan in the early 1980s.

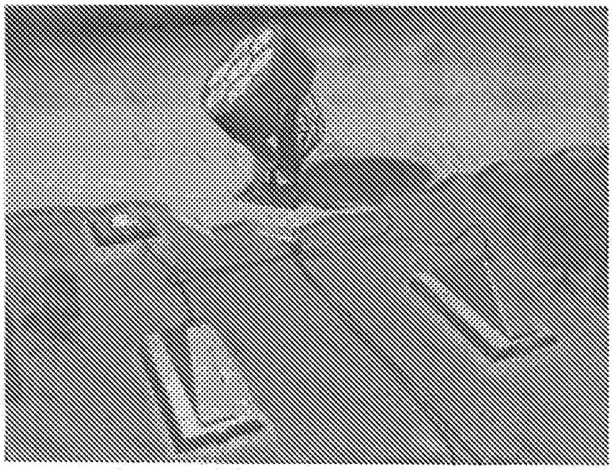

Figure 4. Fresnel-lens collector design approach.

A second design approach is also in the early stages of development by Synertech Systems Corp., New York. It incorporates a proprietary sunlight concentrator that directs sunlight into a reflective lightpipe.

The third design approach, illustrated in Figure 5, was developed by ORNL in 1999. It utilizes a primary mirror and secondary optical element (SOE) to focus visible, nondiffuse solar energy onto a series of centrally located, large-core optical fibers, while at the same time focusing the rejected infrared (IR) solar radiation onto a concentrating PV cell located on the back side of the secondary optical element.

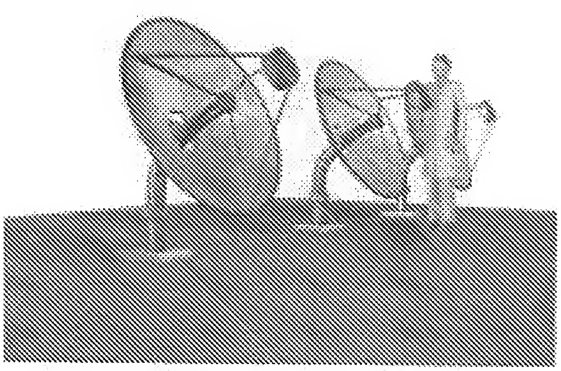

Figure 5. Preferred hybrid solar collector design.

This design incorporates a unique alternative to solar energy use in buildings that views solar energy from a systems-level perspective, integrates multiple interdependent technologies, and takes advantage of the entire solar energy spectrum. It improves the total end-use efficiency by integrating two or more solar technologies into multi-use hybrid systems. The visible portion of the solar spectra is separated from the near IR spectra using a spectrally selective cold mirror. The two energy streams are used for different purposes, that is, lighting and electricity generation. This approach takes advantage of the fact that the conversion efficiency of silicon-based solar cells is much higher in the near-IR spectrum between 0.7 and 1.1-mm (see Figure 1). Similarly, the visible portion of the solar spectrum (0.4 to 0.7 μm) is inherently more efficient in buildings when used directly for lighting (see Figure 2).

Figures 6a and 6b illustrate the preferred design for the hybrid solar collector.

Figure 6a includes numeric references to individual components in the preferred design as follows:

1. ~ 0.8 meter radius primary mirror;
2. ~ 0.125 meter radius SOE with accompanying concentrating PV cell;
3. concentric fiber mount assembly (see Figure 6b);
4. approximately eight 18-mm large-core optical fibers (Note: The size of the primary mirror will dictate the actual number and size of fibers required);
5. angled, hollow mount to reduce range of motion needed for altitude tracking (± ~40° required tracking motion); and
6. a conventional rotational tracking mechanism.

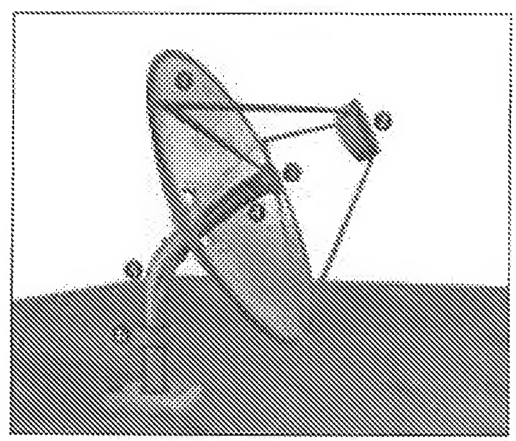

Figure 6a. Preferred design with numerical references to individual components.

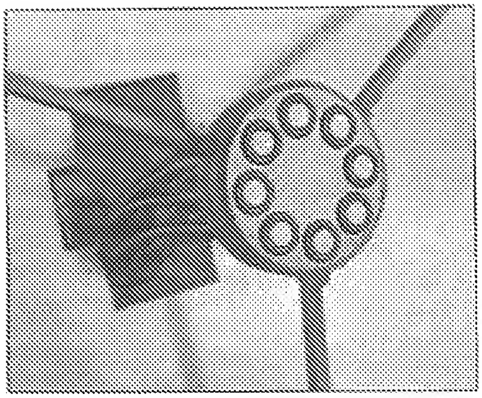

Figure 6b. Close-up view of large-core optical fiber ends.

Compared to earlier designs, the new hybrid solar collector design approach provided several advantages:

1. fewer, easily assembled, system components integrated into a smaller and more compact design configuration;
2. improved IR heat removal and management;
3. improved optical fiber placement and articulation (bundled and pivoted about a radial axis);
4. a longer optical path for incoming light that enables a lower entrance angle of visible light into large-core optical fibers;
5. lower overall transmission losses in the accompanying light delivery system;
6. concentrated IR radiation, allowing for convenient implementation of other solar technologies;
7. small roof penetrations allowing for less-costly installations; and
8. flexibility during space reconfigurations.

To determine the expected optical collection efficiency of the hybrid sunlight collection system, an initial optical design analysis was completed on the hypothetical system illustrated in Figure 3.

To provide an early estimate of the difficulty of coupling the sunlight that can be collected with a 1.6 meter diameter aperture into the fibers, the étendue of the sun and the fibers were calculated. The étendue is a purely geometrical quantity and is a measure of the flux-gathering abilities of a system. The étendue of the sun into a 1.6 meter aperture is 105 mm$^2\Omega$. For an 18-mm diameter fiber with an numerical aperture of 0.4, the étendue is 133 mm$^2\Omega$. Theoretically, because the étendue of the (single) fiber is greater, all the light can be coupled to a single fiber. As such, for an eight-fiber system, there was no problem in achieving a high coupling efficiency.

Summarized here is an initial optical design concept evaluated using commercial optical design tools. The fibers are oriented as shown in Figure 8. It uses a parabolic primary mirror with a radius of curvative of 3675 mm. The primary mirror is approximately 1450 mm from the secondary. Figure 9 shows a cross-sectional view of the concept.

The secondary mirror is made up of eight flat sections, as shown in Figure 8, that are tilted 2°. With this configuration the coupling efficiency is about 95%, assuming 100% reflectivity of the mirrors and no reflection losses coupling into the fiber. The only losses are due to the blocking by the SOE. Optimization routines will likely reduce the blocking fraction to less than 3.0% in future designs.

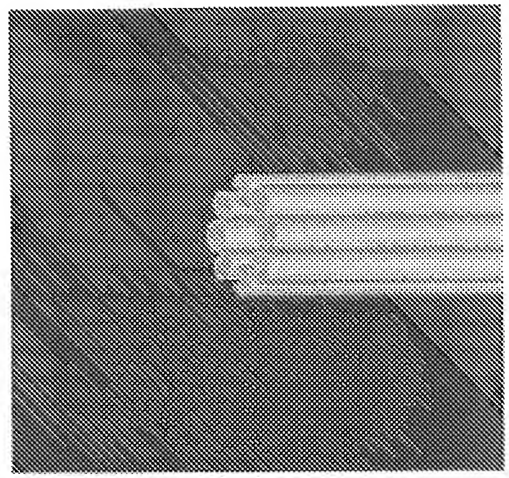

Figure 7. The 18-mm diameter fibers are arranged so that their centers are evenly distributed on a 54-mm diameter circle.

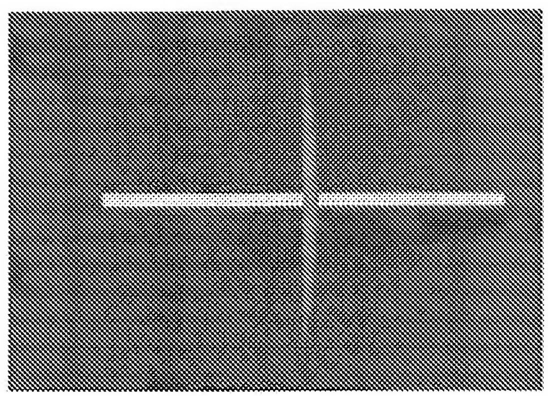

Figure 8. Cross-sectional view of initial design concept with SOE titled slightly (at left).

Projected System Performance

Based on the above design scenario and an associated analysis of performance values for each component, a systems-level performance evaluation was completed. The results of this evaluation suggest that light losses in the proposed lighting system will be approximately 50% for a single-story application and an additional 15-20% for second-story applications. These loss factors take into account losses attributed to the primary mirror, SOE, large-core optical fibers, luminaires, and preliminary estimates for debris build-up and aging of the various optical components.

Relative to the electrical energy displacement efficiency of the system, Figure 9 summarizes the projected performance during peak use periods per 1000 W of incoming solar flux. Note that the electrical energy displacement efficiency is close to 100%. In other words, 1000 W of collected sunlight displaces an equal amount of electricity. At first glance, this might seem unreasonable. However, included in the performance summary are the following considerations:

The sunlight is filtered, the visible portion (~490 W) is used for displacing less efficient electric light, and the near-IR radiation (~360 W) is used to generate electricity.

The luminous efficacy of the displaced electric light (63 lm/W) includes the luminous efficacy of the lamp and dimming ballast (~90 lm/W), the luminaire efficacy (70%); and

The elimination of excess heat generated by electric lights in sunbelt regions, which reduces subsequent HVAC loads by ~15%.[3]

Based on this design scenario and an associated analysis of cost values for each component, a systems-level cost and performance analysis was completed. The current overall system cost for a single-story application is estimated to be ~\$3000 in commercial quantities. This assumes a 2-m^2 collector, illuminating approximately 12 luminaires, covering close to 1000 ft^2 of floor space. This translates into an installed cost of ~\$3/ft^2 and peak performance of much less than \$2/Wp.

When considering the cost and performance of various energy-efficiency approaches, it is often convenient to display them in terms of cost per kilowatt-hour (kWh) displaced. In the case of hybrid lighting systems, this method is dependent on several factors, including the regional availability of sunlight, building use scenarios, and the price of displaced electrical energy. Figure 10 illustrates the available sunlight per square meter incident on a two-axis tracking collector in different regions of the United States.

Table 1 provides the resultant cost of hybrid lighting in terms of cents per kilowatt hour (¢/kWh) of displaced electricity in different regions of the United States over a 18-year lifetime (including periodic maintenance) under differing building end-use scenarios (365, 300, and 250 days per year) and differing levels of sunlight availability (9, 7, and 5.5 kWh/m^2/day). It also assumes that only 80% of the solar flux is in the form of direct, nondiffuse sunlight, and only ~ 80% of the direct sunlight available was used to displace electric light. The remainder of the sunlight will likely not be used because of occupancy controls in buildings and insufficient color matching of natural and electric illuminants. The average cost of electricity during the day, during peak demand periods, is projected by the American Solar Energy Society to be between 10 - 15 ¢/kWh by 2004 in a deregulated marketplace.[4] Using an average value of 12.5 ¢/kWh, we estimated the current and projected simple payback in years based on a 50% reduction in systems and cost once the system is fully commercialized. Similar cost reductions were observed in other solar technologies during their early years of development and commercialization (see Figure 11).

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Table 1. Summary of cost per kilowatt hour and simple payback for hybrid lighting systems in different regions of the United States.

Comparisons with Alternatives

Advanced Electric Lighting

For hybrid lighting to gain widespread acceptance, it must displace a significant amount of inexpensive electrically generated light. Continued advancements in lamp efficacy (~15% over the past decade) and lighting controls will continue to increase their efficiency and reduce the time electric lights are in use. Hybrid lighting is, however, complementary to advanced electric lighting systems, especially those using electronic ballasts and occupancy sensors to reduce electric lighting use. By incorporating the daylight harvesting aspect of hybrid lighting with electronic dimming ballasts and occupancy sensors, the payback period of the ballasts/controls and hybrid lighting systems are both reduced.

Because hybrid lighting systems require the use of state-of-the-art electric lights when sunlight is not available, their cost is additive. As such it is not fully appropriate to compare them directly. However, if one were to do a "head-to-head" comparative analysis, the additive cost of hybrid lighting as defined in table 1 (in terms of ¢/kwh and \$/ft^2) would be competitive and possibly even less in some cases.

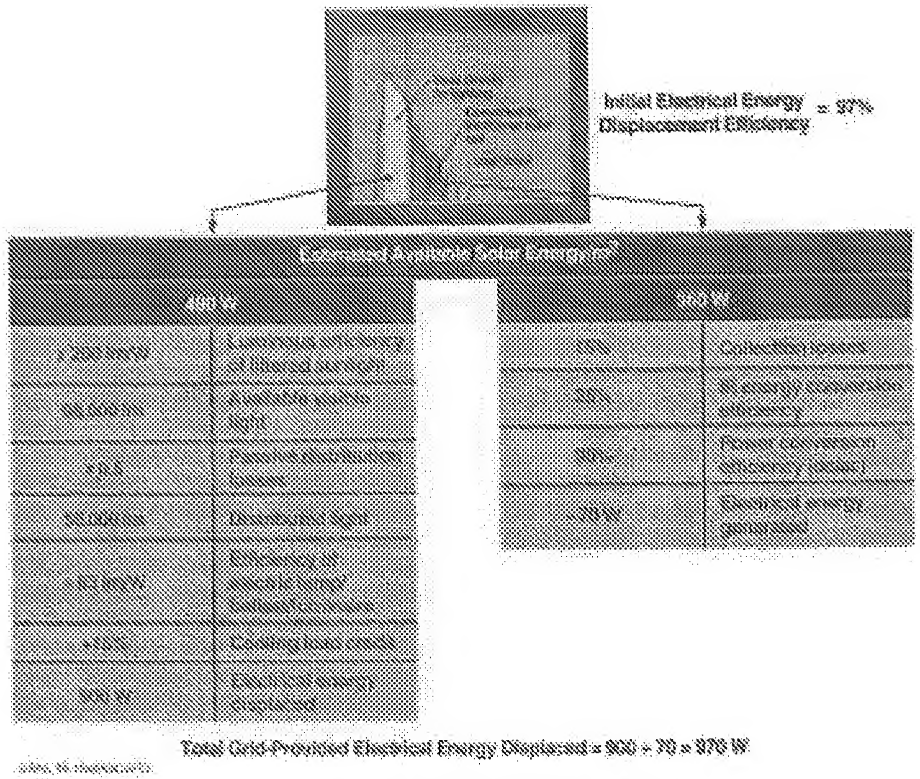

Figure 9. Energy displacement summary.

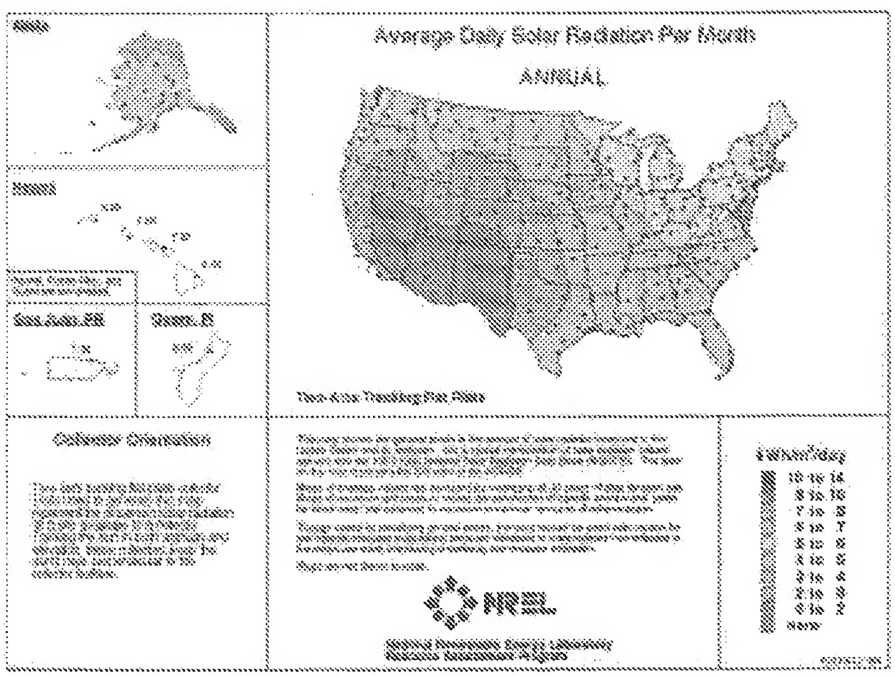

Figure 10. Average U.S. solar availability.

Conventional Topside Daylighting

A complete study of all types of topside daylighting is not warranted for the purposes of a comparative analysis with hybrid lighting. We, therefore, have limited this discussion to skylights, generally accepted as the most cost-effective form of conventional topside daylighting.[5]

On average, incident sunlight does not enter skylights normal to the horizontal plane. Depending on the type and configuration of skylight, light transmission varies dramatically and is attenuated significantly. This is due to several factors but is predominately determined by the efficiency of the light well and glare control media. The typical transmittance of state-of-the-art tubular, domed skylights varies widely, depending on lighting requirements, but for commercial applications is typically well under 50%.

Comparatively speaking, several other factors must also be considered. First, the CU of a single 1-m^2 tubular skylight will inherently be much lower than a system that distributes light from the same square meter to ten or more luminaires. Assuming that the room cavity ratio and other room parameters are identical, the CU of the more distributed hybrid system should be significantly better. If the single 1-m^2 skylight were replaced by ~10 much smaller skylights, the two systems CUs would compare equally, yet the cost of the skylights would increase prohibitively due to the need for multiple roof penetrations and associated installation and maintenance costs.

Second, skylights are typically not designed based on the maximum amount of light that can be supplied but rather designed to approximate that which is produced by the electric lighting system when the total exterior illuminance is 3000 footcandles. Because of this, all light produced by skylights beyond this value is simply wasted. As such, preliminary estimates suggest that on average, depending on location, approximately 30% of the total visible light emerging from skylights is excess light that does not displace electric lighting.

Third, conventional skylights are often plagued by problems associated with heat gain and do not harvest non-visible light as hybrid systems will.

Fourth, conventional skylights are not easily reconfigured during floor-space renovations.

Once all factors are considered, the simple payback (typically >10 years) and energy end-use efficiency of even the best topside daylighting systems is considerably worse than projected hybrid lighting systems.

Other Uses of Solar Energy

To date, the United States has invested billions of dollars in systems capable of converting solar energy into electricity. The most relevant examples include solar PV modules and solar thermal technologies. The advantages of these systems are obvious. First, PV modules require no moving parts to convert sunlight into direct-current electricity, and they can be conveniently used for any electrically-powered end use. Unfortunately, these advantages come with a steep price in terms of overall efficiency. For example, commercial solid-state semiconductor PV modules have a total conversion efficiency of between 10 and 20%. Solar thermal systems typically have a conversion efficiency of between 11 and 25%, depending on system design and complexity. Further, losses attributed to electric power transmission/distribution (~8%) and dc-ac power conversion (~ 15%) further reduce the overall efficacy of conventional solar technologies. Because of these and other reasons, conventional solar technologies have not displaced significant quantities of nonrenewable energy and are expected to be used in the United States for residential and commercial buildings, peak power shaving, and intermediate daytime load reduction.[2] The PV modules currently sell for between \$3 - \$5/Wp.

Ironically, close to 20% of all electrical consumption in the United States (over 30% in commercial buildings) is for lighting; thus, a significant portion of energy generated from sunlight via PVs and solar thermal technologies is ultimately used for lighting purposes. Because electric lamps have a conversion efficiency of 10 to 25%,[3] the overall efficacy of the sunlight-to-interior light conversion/reconversion process is typically less than 5% (see Figure 2).

If the uses of solar technologies are for reductions in energy use in buildings, peak power shaving, and intermediate daytime load reduction, we suggest that hybrid lighting is a more effective way of using solar energy to reduce nonrenewable energy consumption in developed countries like the United States.

As an added benefit, the IR portion of the solar spectrum will be filtered at the sunlight collector. As such, new hybrid collector designs will likely use this energy for generating electricity, water treatment, or the heating of water. This proposed "full-spectrum" use of solar energy is reinforced by the fact that the preferred solid-state material used in PVs (polycrystalline silicon) has a much higher conversion efficiency in the IR region of the solar spectrum.

A preliminary comparison of the projected cost of full-spectrum systems(summarized in Table 1), PVs, and solar thermal electric systems is provided in Figure 11.[2] Given this, full-spectrum solar energy systems represent a realistic opportunity for the United States to rethink how solar energy is used in commercial buildings and accelerate the pace of solar energy technology development.

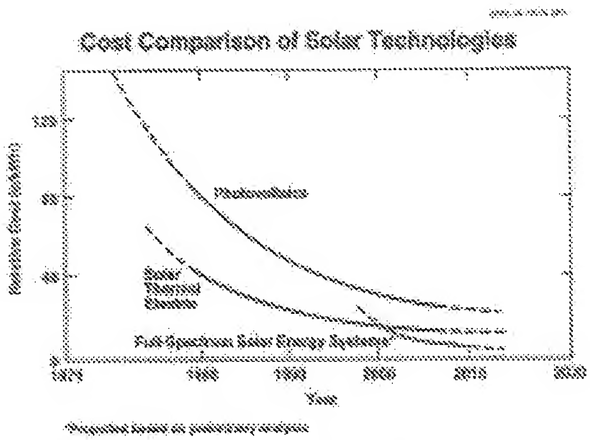

Figure 11. Cost comparison of various solar technologies.

SUMMARY

This paper describes a systems-level design, preliminary performance and cost evaluation of a new approach for improving the energy efficiency and affordability of solar energy in buildings. By using different portions of the solar spectrum simultaneously for multiple end-use applications in buildings, the proposed system offers unique advantages over other alternatives for using sunlight to displace electricity (conventional topside daylighting and solar technologies). Our preliminary work indicates that hybrid solar lighting will alleviate many of the problems with passive daylighting systems of today such as spatial and temporal variability, glare, excess illumination, cost, and energy efficiency. Similarly, our work suggests that the most appropriate use of the visible portion of direct, nondiffuse sunlight from an energy-savings perspective is to displace electric light rather than generate electricity.

Early estimates detailed in this paper point to an anticipated system cost of well under \$2.0/Wp and 5-11 ¢/kWh for displaced and generated electricity in the top floor of a commercial building.

NOMENCLATURE

CU - coefficient of utilization
IR - Infrared
PV - photovoltaics or solar cells
SOE - secondary optical element

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